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Extension of the Usable Engine Life by Modelling and Monitoring

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Summary

After providing some commonly used definitions of fracture critical parts, the influence of improved calculation methods on the design of such components is shown. Various approaches to the determination of usable fatigue life are discussed, particularly the classical safe life philosophy and approaches exploiting the damage tolerance of components. Within this general framework there exist various possible lifing policies, that have to be discussed and agreed between the engine manufacturer, the users and the regulatory agencies. The methods for life usage management may be adapted to changing environments, taking into account the experience gained during operational usage. The introduction of recording or monitoring systems makes it possible to calculate the actual life usage of individual components or at least to determine the scatter of usage within an aircraft fleet. These results enable a specific exploitation of the life potential of the parts without giving rise to an increased risk. The use of the life potential beyond the safe crack initiation life requires experimental and computational methods to gain insight into the fracture mechanical processes governing crack propagation. The corresponding results can also be used to determine inspection intervals that ensure a detection of cracks before those cracks start uncontrolled growth. Results from an on-board life usage monitoring system used by the German air force are presented. An outline of the tasks of usage monitoring is given. Finally some remarks on fleet management are presented.

Introduction

A considerable percentage of the military aircraft and engines now in use have experienced operation over usage times not foreseen when those engines were designed. In Germany we have the F-4F (Phantom II), designed around 1965, that entered service at the German air force in 1974 with its J79 engine. The same engine also powers the F-104S-ASU (Starfighter) still in use at the Italian air force. Both types will continue to fly until being replaced by the Eurofighter. The French air force continues to use the Alphajet and the Mirage F1, both with engines designed in the early 70's. Although many of the older MiG and Su types have been withdrawn from service in the last years, there remains a large amount of aircraft that have seen more than a quarter of a century of operation in the air forces of Eastern Europe. The vast majority of aircraft operated by the NATO nations is more than 15 years old. As engines typically contribute 30% of the life cycle cost of an aircraft, methods aiming at an extension of their usable life attract a widespread attention. There have been various conferences and working groups on this topic initiated by the RTO [RTOMP17, RTOTR28]. All topics of this presentation are addressed in great detail in unclassified sources, some of which are put together in the references, and I strongly recommend to retrieve at least some of the available material from the world wide web.

Definition of fracture critical parts

A typical definition used by regulatory agencies in civil aviation is the one given in [JAR-E]: "Where the failure analysis shows that a part must achieve and maintain a particularly high level of integrity if hazardous effects are not to occur at a rate in excess of Extremely Remote then such a part shall be identified as a Critical Part". "Extremely

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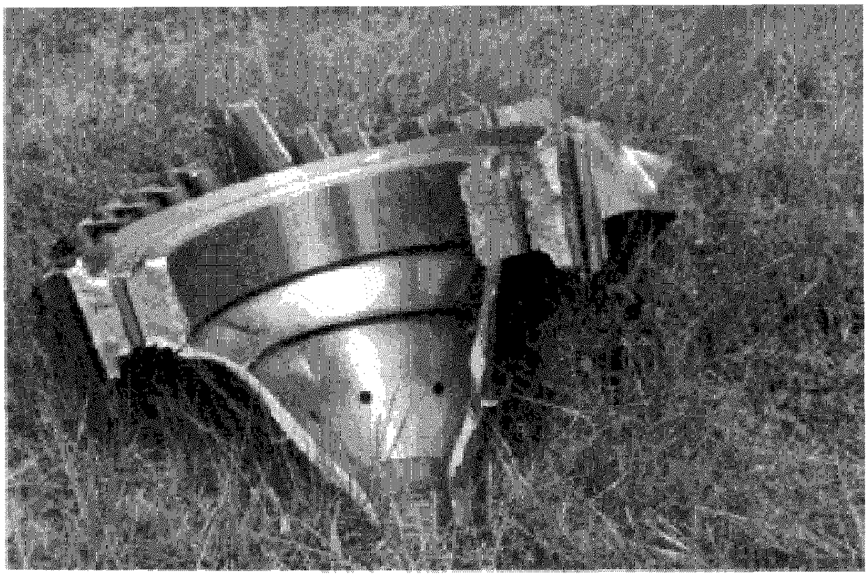

Fig. 1: Largest fragment of fan hub after burst (Pensacola accident)

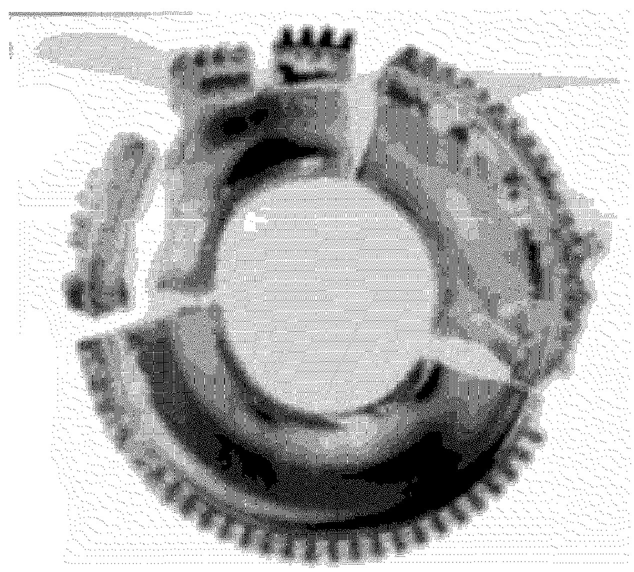

Fig. 2: Disk driven to burst during overspeed spin test

Remote" probability means [JAR1] "unlikely to occur when considering the total operational life of a number of aircraft of the type in which the engine is installed, but nevertheless, has to be regarded as being possible (10^{-7} - 10^{-9} per hour of flight)". In the glossary of [RTOTR28] the following definition is given: "A part which will physically break, causing catastrophic damage, after experiencing a statistically described number and mix of missions. Such components are identified at design time, and removed from service before failure occurs."

The engine parts most likely to cause severe damage to the aircraft are the components of the rotors, the most massive ones being the compressor and turbine disks, but also including spacer rings or rotating air seals, that may sometimes also penetrate the engine casing when a failure occurs. Engine design usually is required to ensure containment of broken single blades, but also numerous incidents with uncontained fan or turbine blades have been reported (e.g. [WB96, JSSG2007]). Although the focus will be on disks, many aspects of the following presentation are applicable to blades as well. Unfortunately, actual disk failures are not limited to experiments performed in the test beds of engine

manufacturers (see example in Fig. 2), but they also happen in the engines of commercial passenger jets with hundreds of passengers aboard. Fig. 1 shows a fragment of the fan hub, whose failure killed two passengers aboard a MD-88 in Pensacola, Florida, in 1996 [NTSB98]. There is a not too short list of other uncontained disk failures in the engines of civil aircraft. Many of them occurred during the run-up to takeoff power of the engines on ground, thus limiting somewhat the possible consequences, but aircraft have been destroyed by subsequent fires, as in the Valuejet accident in 1995 [NTSB96], and there was one catastrophic in-flight failure of a fan hub, claiming the lives of 111 persons. The direct cost of that crash of a DC-10 in Sioux City in 1989 totaled over 300 million US$ [Hall97].
A recent (June 2000) uncontained failure of the HP compressor spool of a GE CF6-80, that happened during takeoff of a Boeing 767 in Sao Paulo, Brazil, led to the recommendation to remove certain engines from service to perform inspections to detect possible cracking.
The military flying community is affected by failing fracture critical parts as well. The following description, which gives a typical example for the consequences of an uncontained disk failure during flight is cited from the Flying Safety Magazine of the United States Air Force [Woo96]:
"The one T-38 engine-related Class A mishap was from another known problem, compressor disk corrosion. A crack propagated from a corrosion pit in the No. 1 engine's eighth stage compressor disk. When the disk eventually failed, it penetrated the case, severed several fuel and oil lines, and caused an in-flight fire. The shrapnel and fire affected the mishap aircraft's flight controls, forcing the crew to eject. The aircraft crashed in an apartment complex, killing two and injuring several other civilians. The source of the corrosion is still unknown. Oddly enough, no other users of the J85 engine have reported corrosion, including the Navy. Regardless, life limit reductions are being implemented to reduce the risk. Corrosion-resistant coatings and materials are also being explored." This short report bears nearly all ingredients of what may happen and what consequences are typically deduced. It also highlights the problem of corrosion, that may invalidate the results of sophisticated life extension schemes.
Disregarding disk failures due to overspeed which might occur after a total malfunction of the control or fuel system or due to a broken shaft in the engine, disk failures usually are the final consequence of underestimated and undetected material fatigue. Even in initially defect-free parts cracks may start to grow at highly loaded areas of the rotor structure. If cracks remain undetected and operation of the part is continued, even normal cyclic loading will eventually lead to an unstable crack growth. The final burst, that results from insufficient residual strength of the heavily cracked disk under high load will produce a few (typically 3 - see Fig. 2 and [DK99]) high energy fragments, that will inevitably penetrate the engine casing, with a high chance for mission abort, air vehicle loss, and fatalities.

Evolution of the design process

The tools available for the design of aero engine components have seen a dramatic evolution during the past 30 years. The finite element (FE) method is now used to determine (and avoid) in advance the locations of high stress concentrations. For most of the old engines, that were designed before 1970, such computer based tools were only available to a very limited extent. At that time the design of rotors was largely based on empirical methods, supported by experiments (e.g. photoelastic strain analysis). The limited accuracy of the available computation methods for temperatures and stresses had to be compensated by the selection of larger safety margins. Only since the middle of the 70's FE programs were used for the stress calculation of rotor components. It became possible to design disks which were stressed more evenly, than it was possible with the classical empirical procedures. Modern design methods try to minimize weight and to fully exploit the available strength of materials. "Old" rotor components often have only a few, clearly identified critical life-limiting areas, whereas a larger number of potentially life-limiting areas has to be taken into consideration for newly designed "fully stressed" components.
The evolution of computational methods within the last 20 years is illustrated in Figs. 3 and 4. Fig. 3 shows a finite element mesh that was used for the axisymmetric stress analysis of the IP compressor rotor of the RB199 engine during rotor design in the year 1979. The same component has been reassessed in 1999 to check for possible life extensions. The refined mesh shown in Fig. 4 partially removes the necessity to apply empirical stress concentration factors to take into account geometric details not resolved by the coarse mesh. In 1979 stress engineers had to wait days for the computation results. With modern workstations a time dependent stress analysis, including thermal stresses and a life assessment for the whole design mission can be run within a few minutes. Fig. 5 shows an example

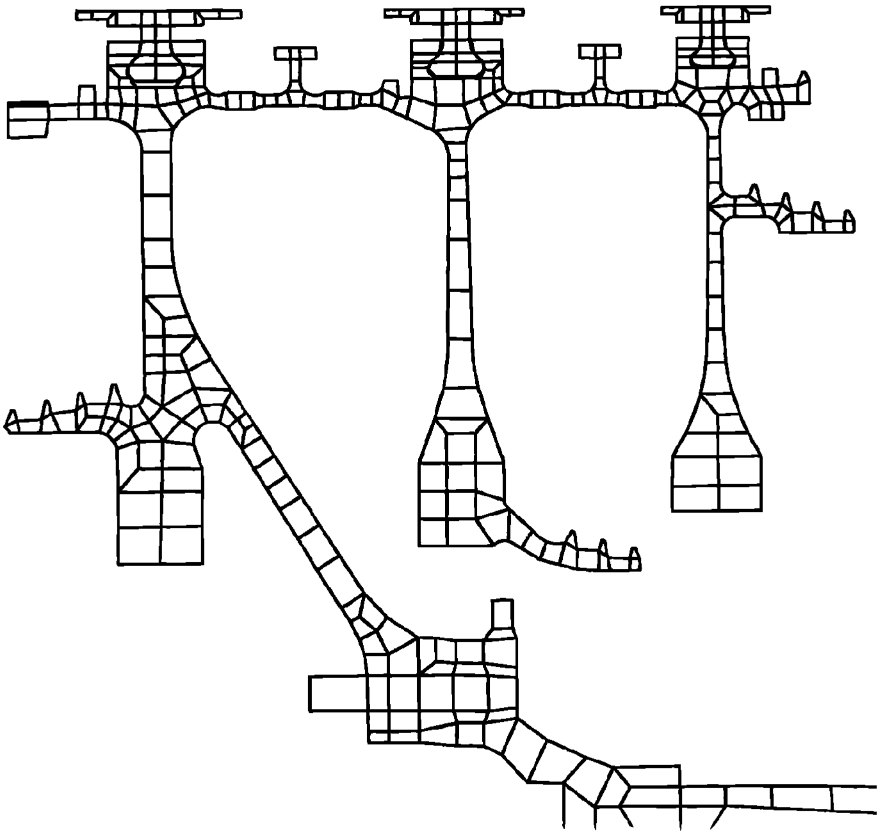

Fig. 3: Compressor rotor, finite element mesh for axi-symmetric stress calculation in 1979

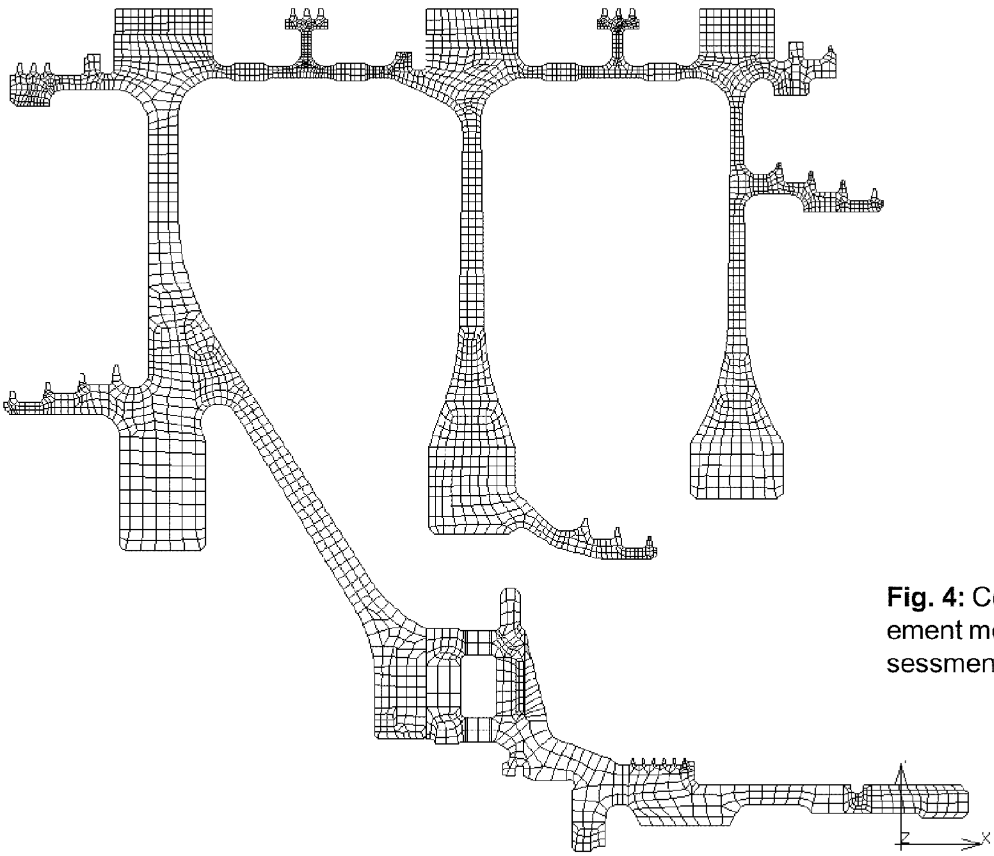

Fig. 4: Compressor rotor, finite element mesh used for recent re-assessment of stresses

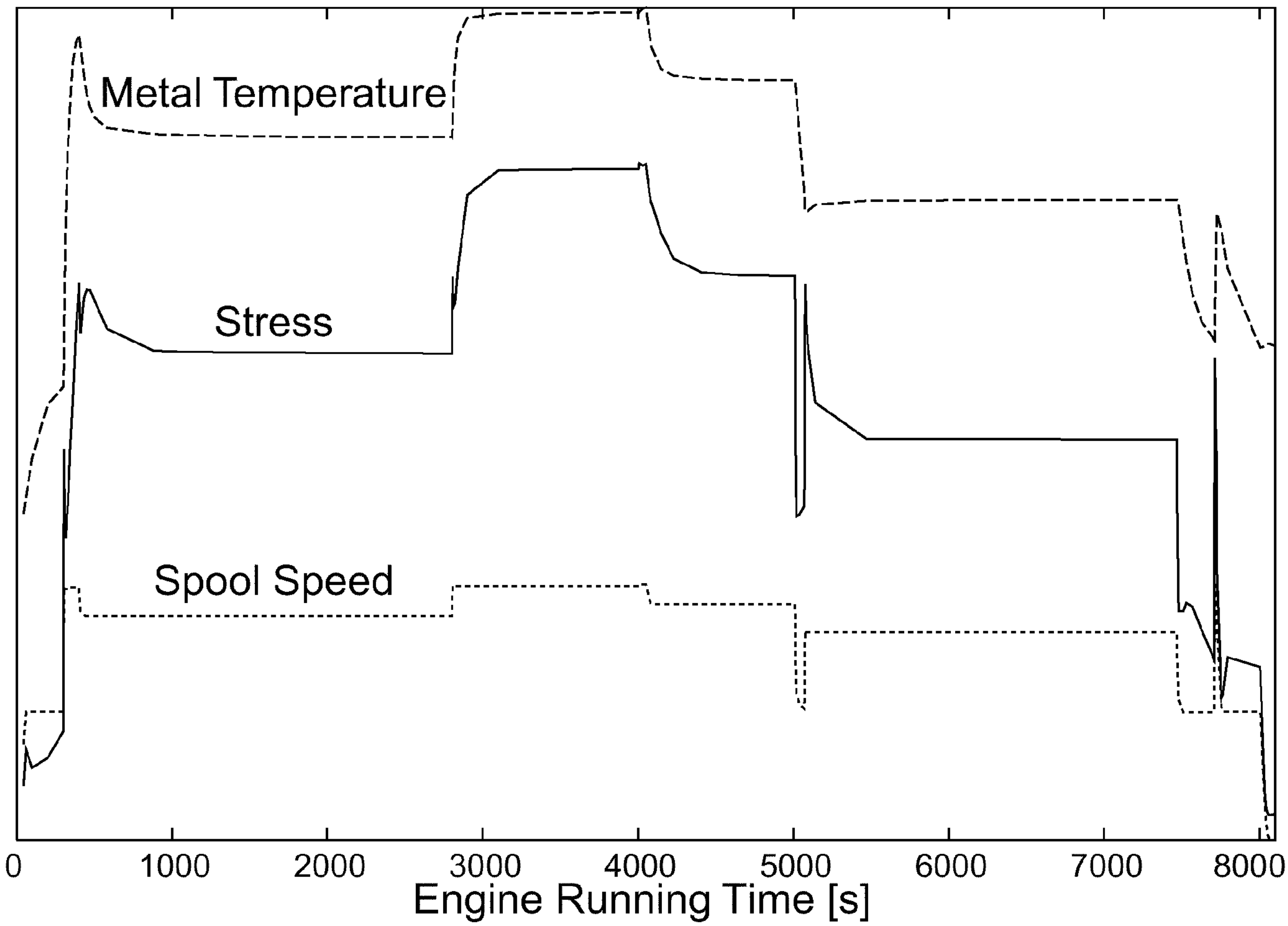

Fig. 5: Design mission: Results of finite element calculation for one critical area

of the calculated temperature and stress at a critical area, together with the spool speed for the design mission. Per definition, the largest stress cycle of this mission is used as reference for LCF life counting for a certain critical area. The life usage of this cycle is set to a value of 1.0. Life releases are expressed as multiples of this cycle.

Safe life versus damage tolerance design

Currently the most widely used lifing policy is that of "Safe Crack Initiation Life". This is the classical method for lifing in the low cycle fatigue regime. The idea of the concept is as follows: It is assumed, that a new part is free of defects. Under operational loading a defect (e.g. a fatigue crack) is generated. When the defect has been generated, the part's life is expired. The life end criterion is a certain predefined crack depth (e.g. 0.4 mm). The usable life is defined as the life of the weakest individuum of a population of parts. As a result of experiments and experience, a lognormal distribution of lives to first crack (LTFC) with a ±3sigma scatter factor of 6 is assumed for conventional disk materials. The method is illustrated in Fig. 6, showing schematically the scatter band of the S/N curves of a large number of similar parts. Due to the requirement for an acceptably low statistical probability (e.g. 1/750) for the existence of a crack with the predefined depth, only a fixed portion of the average life is available for operational use. There is no check for the presence of the life limiting crack, when parts are retired. Details of the method are discussed in [BLH98]. One shortcoming of this method is its inability to predict a failure margin. The method tacitly assumes, that a 0.4 mm crack is sufficiently far away from growing in an uncontrolled manner. This is the starting point for the so-called damage tolerance concepts. It is assumed, that even a new part may have an initial defect, which behaves like a crack

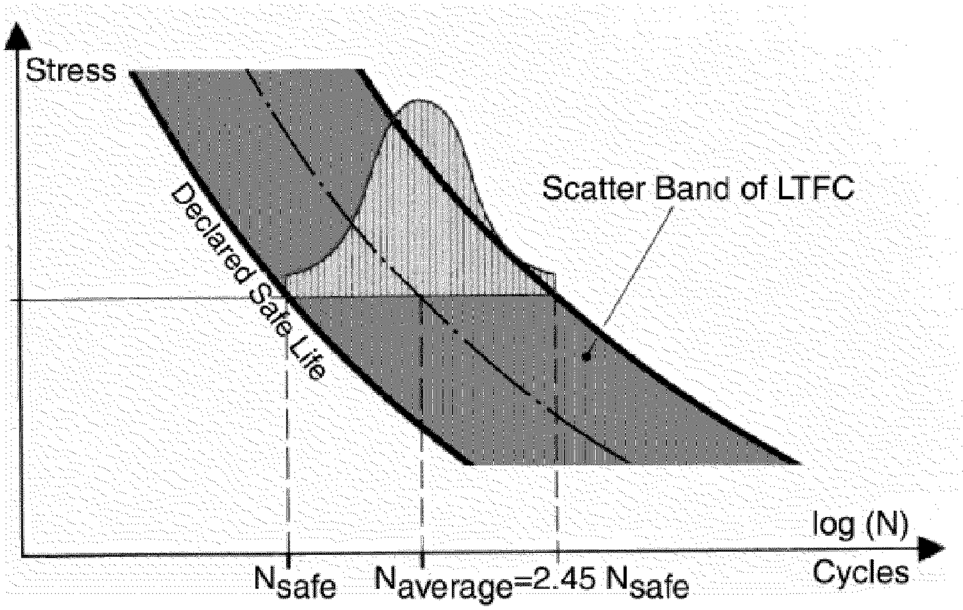

Fig. 6: Distribution of cycles to crack initiation

of a certain depth. This crack propagates under operational loading. When the crack enters a phase of unstable growth, the part's life is expired. The application of a damage tolerant lifing policy requires an understanding of the crack growth process. Experiments and fracture mechanical methods have to be combined to determine the number of load cycles needed to propagate cracks at the critical areas from the assumed initial size to a size implying the risk of disk burst (dysfunction). There are various criteria for dysfunction of a part [BB98]: Unstable crack growth under basic operational loading, onset of continuous crack propagation due to superimposed vibratory stresses, loss of overspeed capability (insufficient residual strength), unacceptable out-of-balance conditions.

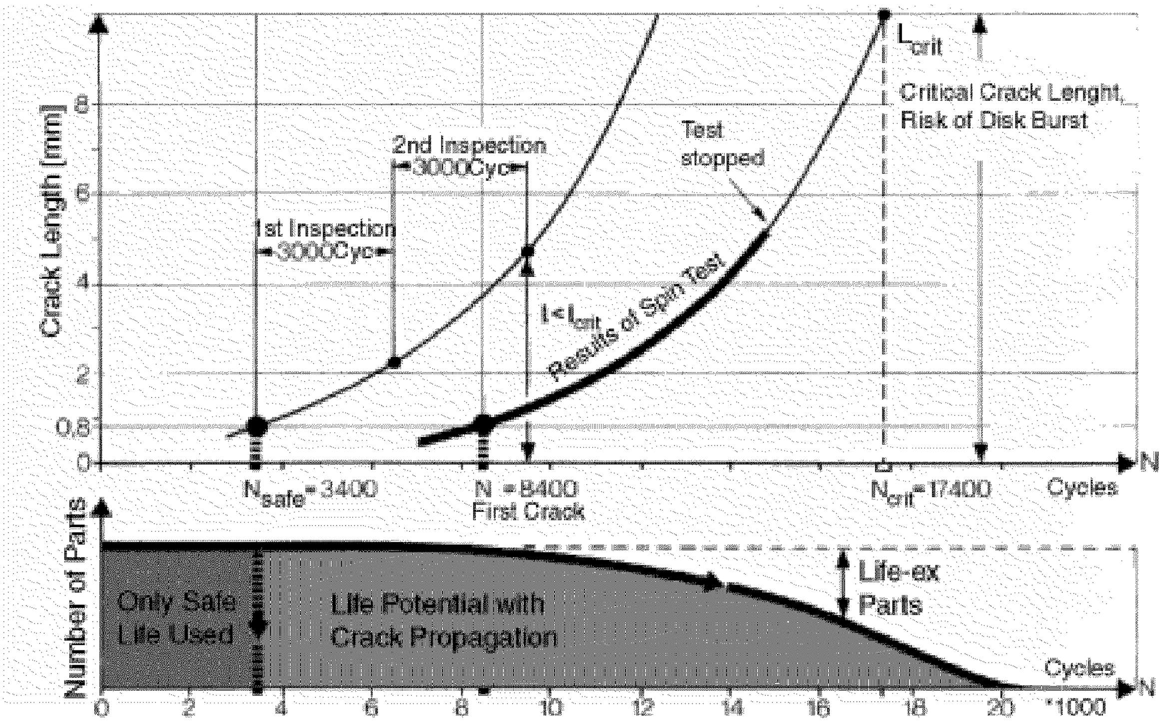

Fig. 7: Life extension into the crack propagation regime

The information about crack growth can be used in different manners. The first method is an extension of the "Safe Initiation Life" concept, called the "Safe Crack Propagation Life". This method is described in [BB98]. The "Initiation Life" criterion (e.g. occurrence of a 0.4 mm crack) is replaced by the "2/3 Dysfunction Life" criterion. For crack tolerant components having a long crack propagation life, significant life extensions compared to "Initiation Life" are possible. On the other hand the application of the "2/3 dysfunction life criterion" to components with low damage tolerance may even require a reduction of the life figures derived from the "Initiation Life" criterion. This is necessary to ensure a consistent safety margin.
All of the methods described so far do not exploit information from inspections. Parts are scrapped when they have reached their released lives irrespective of the actual presence of cracks. If reliable nondestructive inspection (NDI) methods are available, that are able to guarantee defect sizes below prescribed limits, then the method illustrated in Fig. 7 is applicable. A part can be returned into service, if it is found defect-free or the defects are so small, that the expected crack propagation period is longer than the planned inspection interval.

Lifing policies

The lifing policy that will be applied to a new engine is usually discussed and agreed by the contractors. As already mentioned, the most commonly used lifing policy in Europe is the "Safe Life" approach. In this method only a chosen percentage (e.g. 50%) of the calculated expected life is released at entry into service of a new engine. This applies also to the introduction of engine or component modifications, that are judged to significantly influence the life of the affected components. Evidence has to be provided by performing spin pit tests with full scale components, by which the component is subjected to a series of cyclic load changes. The load levels are chosen to exceed the expected operational loads by a chosen, usually moderate percentage. This overload provides some safety margin against uncertainties in the stress calculations and it also serves to shorten test times, that are a substantial cost factor during component qualification. Spin tests are continued until cracks start to grow at critical areas of the disks.
If the need arises, the test may also be continued into the crack propagation regime, however requiring some extensions of the experimental planning and evaluation (e.g. application of marker loads, determination of crack geometry). This is necessary to produce the data required for a prospective inclusion of the parts crack growth potential into an extended life release.
Dependent on the number of tested disks and on the achieved number of test cycles, at first only a certain percentage of the life demonstrated in the spin test is released. Safety factors have to be included taking into account the very small (typically not more than 2 or 3) sample size. Spin tests are continued in parallel to the operation of the engines in the users' fleets. Based on an extrapolation of usage data, that may either consist of cycles accumulated by engine monitoring systems or simply based on the number of flights or accumulated flight time, required schedules for life releases are determined. When the first components have reached the life released so far, at least one of those components is removed from service and it is then tested for remaining life in a cyclic spin test. The new results are used to release a further portion of the life. This process is continued, until 100% of life can be released.
The formal life release usually is authorized by a regulatory agency based on available evidence. In contrast to commercial aviation, where international standards (e.g. [JAR-E]) are applied, it is quite common in military aviation, that different users of the same engine types use different methods of life releases or even different lifing policies. Lifing philosophies may be different within one country: In the USA, the US Air Force practices the damage tolerance philosophy, whereas the US Navy practices the safe life approach.
There is a number of reasons for an enhancement or modification of the existing methods. Possible extension are the inclusion of test results from other sources than spin-pit tests, e.g. specimen tests, an improved statistical approach [BLH98] to take into account so-called non-finite test results (i.e. no crack has occurred at some intermediate stage of the cyclic spin pit tests).
Experience from a number of projects shows, that it is not always possible to take into account all life limiting areas in the initial assessment of a new or redesigned component. If cracks occur at unexpected locations (either during the spin-pit tests or during operational use), those areas have to be introduced into the defined lifing process or they have to be treated by a different method, e.g. scheduled inspections.

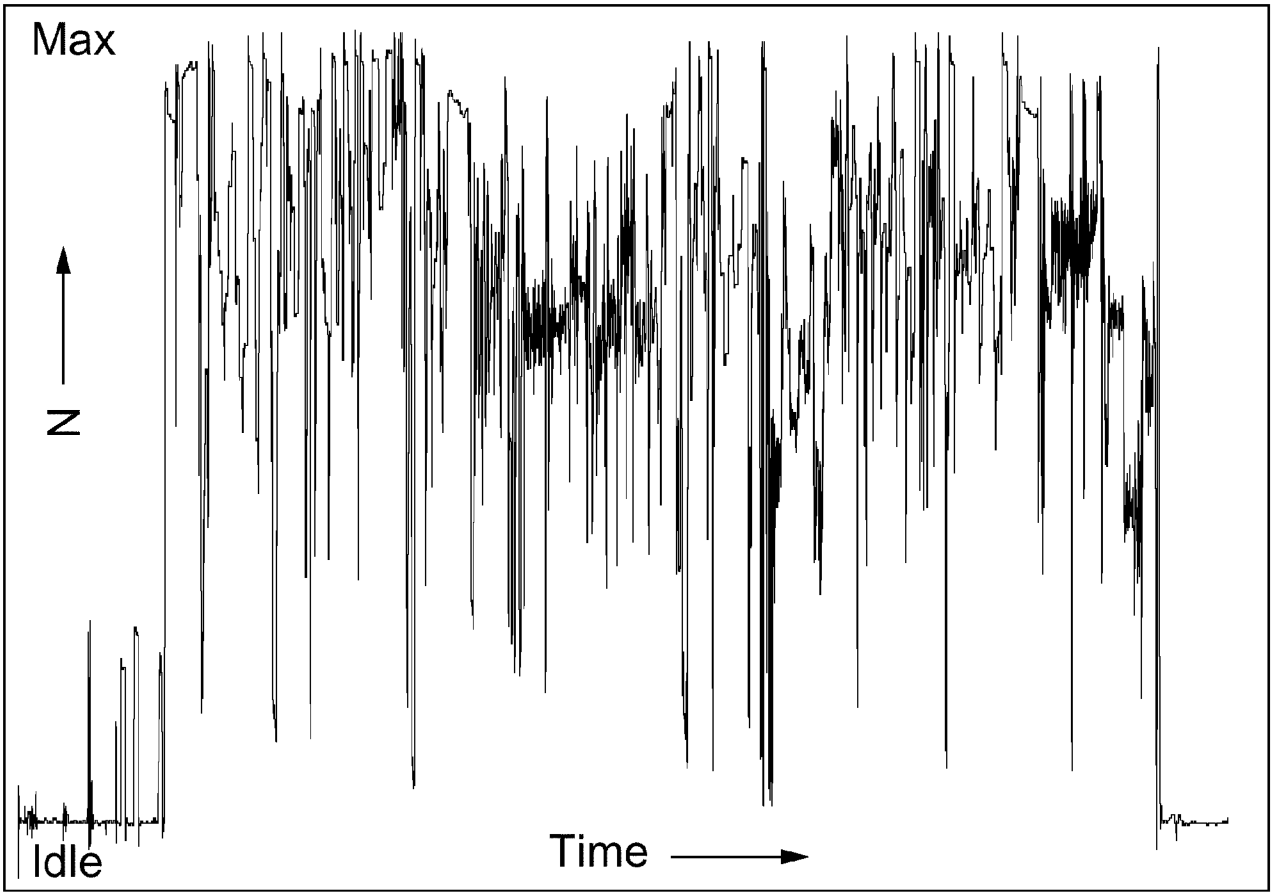

Fig. 8: Spool speed of real mission

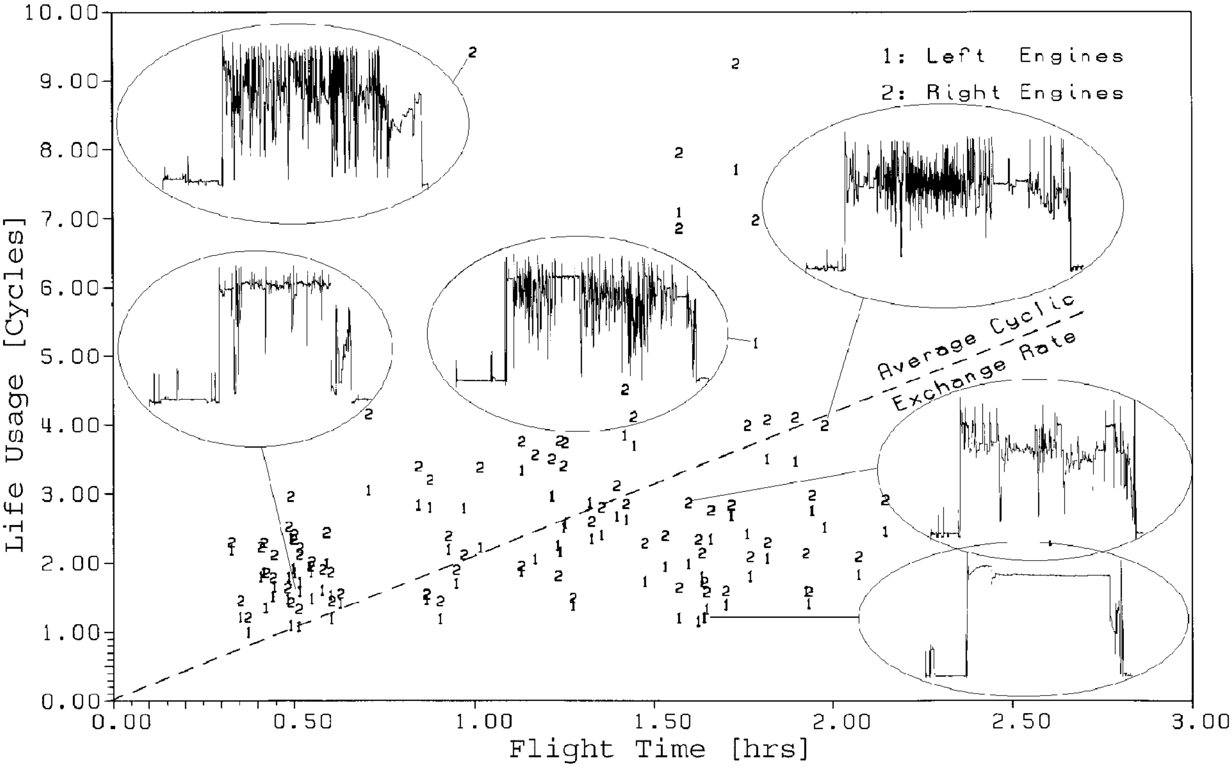

Fig. 9: Distribution of single flight life usage

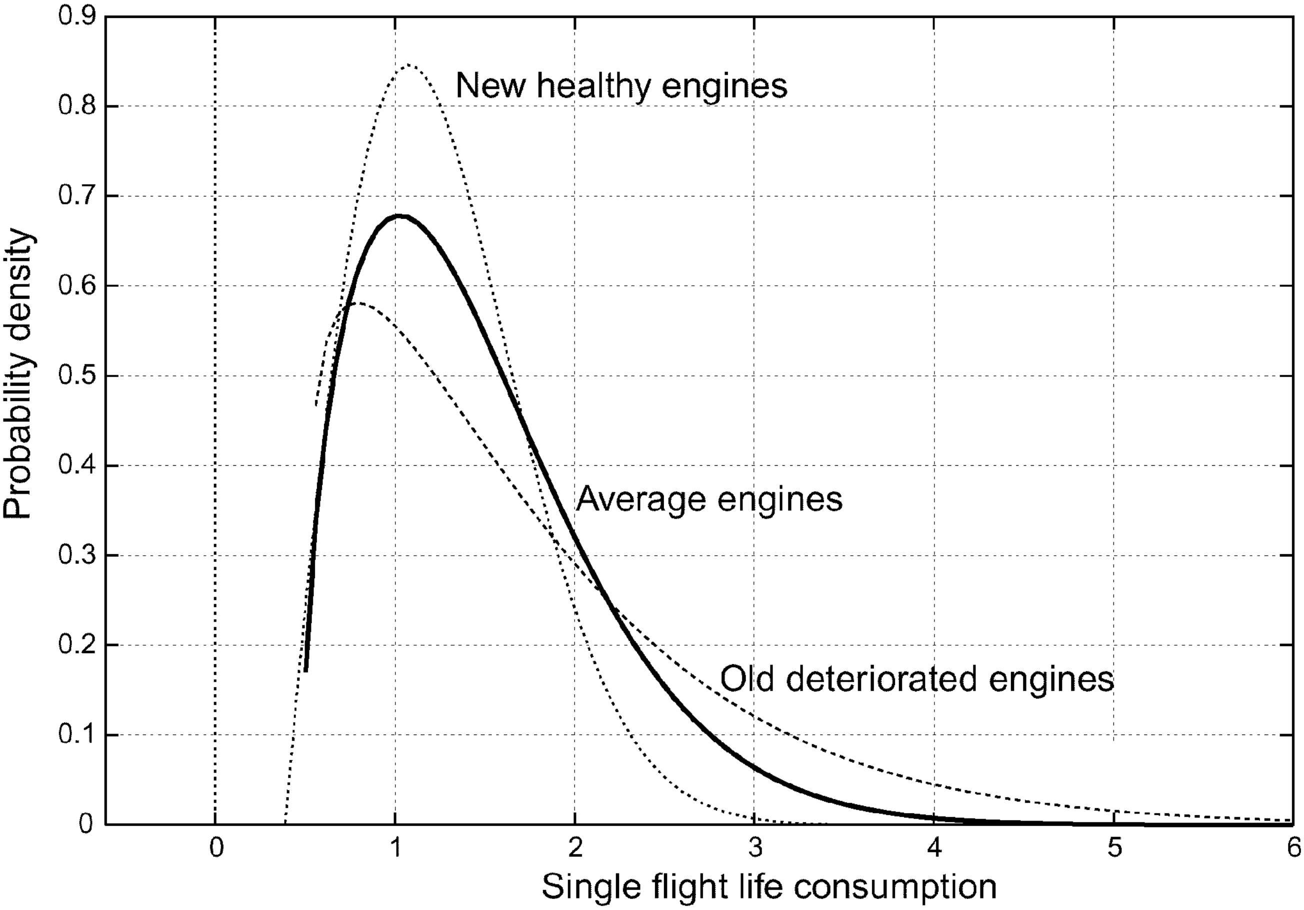

Fig. 10: Assumed shift of life consumption distribution for aging engines

For the RB199 engine the "Safe Initiation Life" policy was initially chosen. During the first years of operation, cracks were found at some unexpected areas of the rotors. If treated with the original method, the affected components would have to be retired long before reaching their expected life limits. To recover some of the life potential, the damage tolerance at the newly detected critical areas was assessed. The application of the "2/3 dysfunction life criterion" may restore the originally expected usage times, if the crack propagation life extends over a sufficiently large number of load cycles. The application of the "Safe Crack Propagation Life" to the IP compressor and the IP turbine of the RB199 is described in [BB98].

If cracks occur at locations with lacking damage tolerance, it is also possible to integrate inspections into the lifing process. In some circumstances inspections may also be required, if only a limited number of parts behaves different from the rest of the population. If deviations in the production process have occurred, whose influence on life was not known at production time, the information required to decide on possible life reductions may only accessible by an inspection.

Adaptation of the lifing process to in-service experience

The first experience in nearly every military engine project is the realization, that there exist non-negligible differences between the design missions and the actual usage. Although design missions have become more realistic for newer projects (see e.g. [JSSG2007]), it is nearly impossible to cast usage patterns similar to those of Fig. 8 into manageable specifications. Data recordings taken during the first time of in service usage may be used to determine the scatter of life usage caused by different missions. An example (Fig.9) from [BP97] shows, that the assumption of a life usage

proportional to flight time does not hold for single flights. A better approximation is to determine probability distributions describing the life usage per flight (Fig. 10). Due to thrust requirements for take off, life usage per flight is always greater than some minimum value for most of the critical areas.
The requirement for maintaining some prescribed thrust level is also the reason, that we have to assume some shift of the life usage distributions for aging or deteriorated engines (Fig. 10). If the control system tries to maintain the thrust level by increasing engine temperature and speed, usage will be more severe due to increased thermal and mechanical stresses and also due to lower life potential of the materials at higher temperatures, even if no change in mission types occurs.
There are numerous parameters, by which the use of a component can be described. Flight time, engine running time, number of flights, number of engine runs, engine running time above certain spool speeds, time at certain temperatures. More appropriate for a description of the usually life limiting processes are parameters approximating the cyclic properties of engine operation. The best known method is the counting of so-called TACs (total accumulated cycles) mainly in use at the USAF.
Because of the somewhat arbitrary definition of the power ratings this procedure can be refined by admitting arbitrary spool speed values in the assessment of the contribution of a spool speed cycle. The method outlined below is an extension of counting TACs. If it is implemented in an on-board monitoring system or in a ground-based system for the assessment of recorded engine data, the results are directly comparable with specification values using TACs as a measure for cyclic engine or component usage. The method for "continuous TAC cycle counting" consists of the following steps:
1) Calculation of non-dimensional spool speeds $N = N_{phys} / N_{ref}$, where N_{ref} is the 100% spool speed, equivalent to the "intermediate rated power" (IRP) used in the definition of the "Type I, III, IV" cycles [JSSG2007].
2) (N_{min}, N_{max}) cycle extraction for the selected spool speed signal with a rainflow method, using one of the available very efficient methods for real-time cycle extraction. The rainflow method replaces the simple gate based counting used in the original TAC definition.
3) Computation of hypothetical stresses for the extreme values of the cycle, i.e. $S_{min} = N_{min}^{2}$, $S_{max} = N_{max}^{2}$.
4) Assumption of a maximum (e.g. burst) speed N_{lim} and a corresponding hypothetical stress $S_{lim} = N_{lim}^{2}$ and of a hypothetical "endurance limit" $S_{cut} = S_{lim} \cdot FCUT$, where $FCUT$ is a chosen percentage of S_{lim}. Cycles $(0,S_{max})$ with $S_{max} < S_{cut}$ contribute zero usage. The endurance limit is defined as the maximum applied cyclic stress amplitude for an 'infinite' fatigue life. Generally 'infinite' life means more than 10 million cycles to failure.
5) Conversion of the (S_{min}, S_{max}) cycle into an equivalent $(0,S_{eq})$ cycle with the Goodman formula
$S_{eq} = S_{lim} \cdot (S_{max} - S_{min}) / (S_{lim} - S_{min})$
6) Calculation of an auxiliary stress $S_{aux} = S_{eq} / S_{cut} - FCUT$
7) Calculation of the hypothetical damage of the found spool speed cycle $D = (S_{aux} / (1 / S_{cut} - FCUT))^{ESN}$, where ESN is an assumed slope of a hypothetical S/N curve.
The parameters in the formulas above can be chosen to closely match the definition of TACs provided in [JSSG2007] or in the appendix of [RTOTR28]: $TAC = LCF + FTC/4 + CIC/40$,
where LCF = "Engine Start to IRP to Engine Stop Excursion", FTC = "Idle to IRP to Idle Excursion",
CIC = "Cruise to IRP to Cruise Excursion".
The following parameter settings match the TAC definition assuming the spool speeds of the HP spool of the RB199 engine (Idle=65%, Cruise (assumed)=81%): N_{lim}=120%, $FCUT$=0.55, ESN=3.5. With this definition a (65%,100%) cycle will produce a usage of 0.25, a (81%,100%) cycle will give usage 0.025.
For engines with 2 or three spools, it is advisable to use separate definitions for the different spool speeds, since the percentage values of idle and cruise will be significantly different for HP and LP spools. The definition N_{lim}=130%, $FCUT$=0.4, ESN=2.0 is a choice giving higher weight to "sub-cycles". The results for the two selected parameter settings are shown in Fig. 11 for $(0,N_{max})$ cycles and in Figs. 12 and 13 for arbitrary cycles.
A cycle counting system using the above mentioned or similar parameters would produce consistent usage figures, that allow the recognition of changing usage due to new tactics, operational procedures, pilot training etc. However, it must be emphasized that TAC cycle counting provides only a gross measure of usage and cannot fully replace monitoring functions specifically tailored to the thermomechanical behaviour of the critical parts.

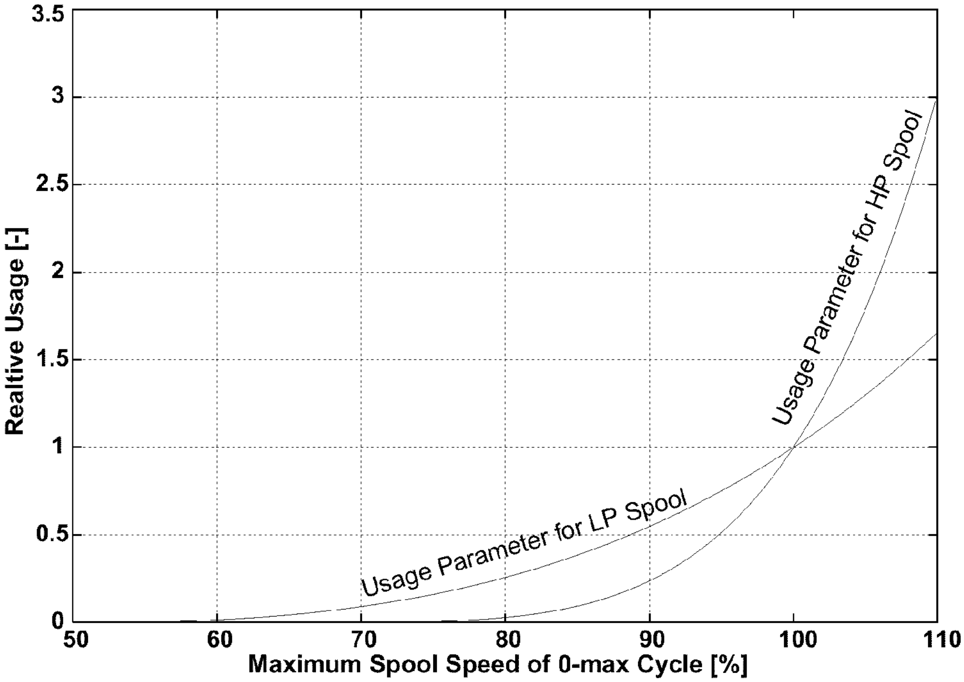

Fig. 11: TAC equivalent of arbitrary 0-max spool speed cycle

The impact of recording and monitoring systems

Without information on the usage of an engine in service, very conservative assumptions have to be made with regard to the life usage of critical parts. If a new or modified engine is introduced into service, a commonly used method is either to assume a certain mission mix composed of the specified design missions, or, somewhat better, to use recordings from flight tests to substitute the missing information on usage in service. From those assumed or recorded data, the life consumption at all critical areas of the engine rotors has to be computed. However this requires mathematical models of the thermal and mechanical behaviour of the rotors suitable to calculate the life consumption for arbitrary input data. Such simplified models have to be derived from the complex finite element models used by the manufacturer during component design.

If no life usage monitoring system is used, the common practice is the assignment of conservative life usage figures to all critical areas. Each area then has a so-called ß-factor (average cyclic exchange rate) describing the life usage per flight hour or some other easily available usage figure (e.g. engine running time, number of flights). The fatigue life consumption at a critical area is then computed by a multiplication of the ß-factor with accumulated flight time. The accumulated cycles have to be compared with the released lives. A part is removed from service, if either the life limit is reached or if the part is accessible during maintenance and the low remaining life makes the reuse of the part uneconomical.

A more accurate determination of cyclic exchange rates can only be obtained from a sufficiently large number of flight and engine data recordings, with some side conditions concerning data quality, availability of configuration information and statistical significance (e.g. data from different engines, air bases, mission types etc.). With those data, it is possible to derive statistically meaningful data on the usage scatter within the fleet for each critical area of all critical parts.

Risk mitigation techniques

The most popular and probably most costly risk mitigation technique is a regular inspection of all candidate locations for fatigue cracks, using NDI methods. This is currently performed in the commercial aviation world for certain components of older engines known to be at higher risk level due to deviations either in the material properties, in the

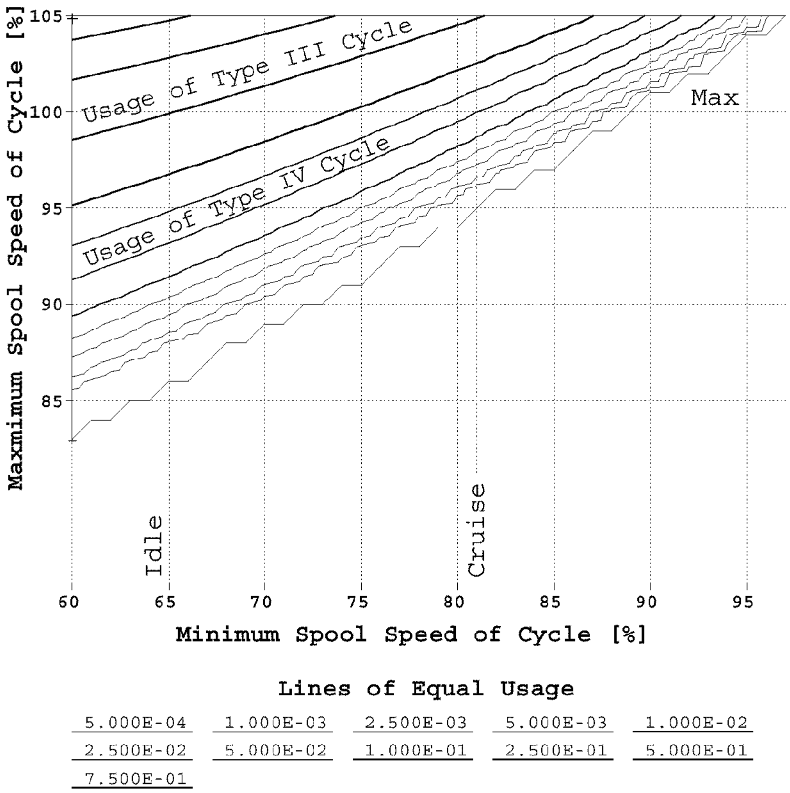

Fig. 12: TAC equivalent of arbitrary HP spool speed cycle

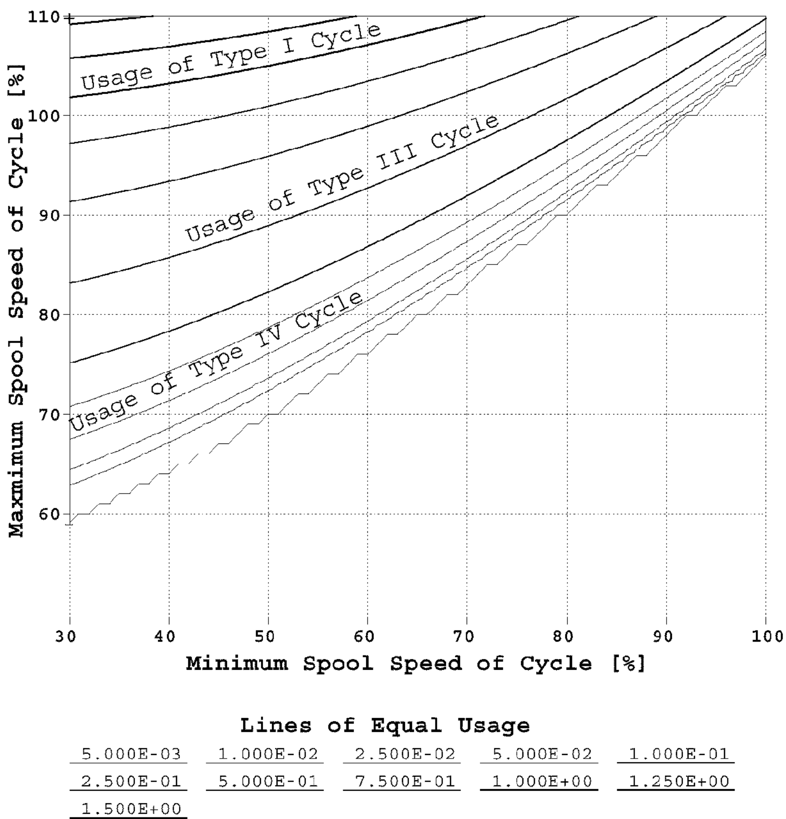

Fig. 13: TAC equivalent of arbitrary LP spool speed cycle

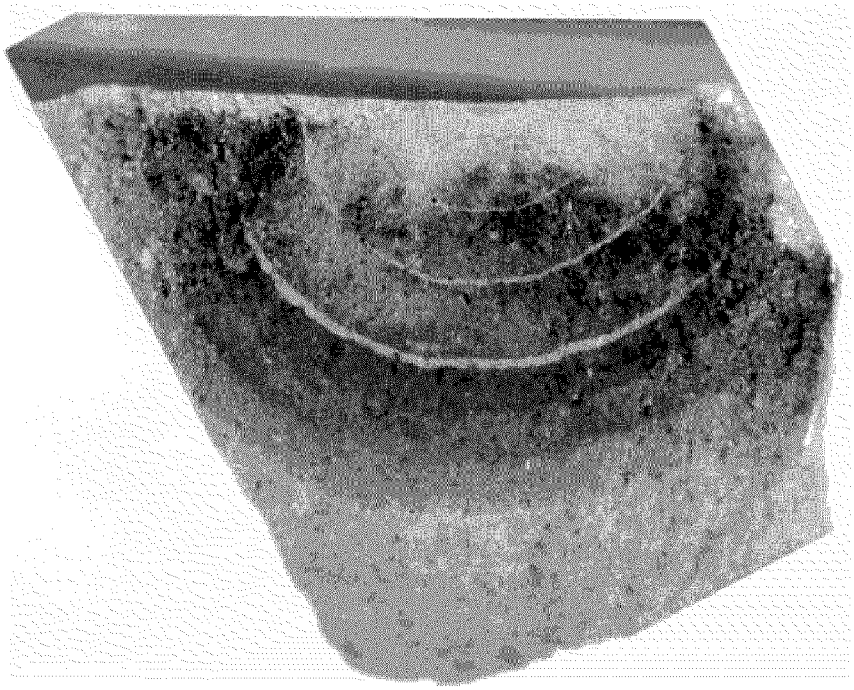

Fig 14: Measured crack growth history for rim area

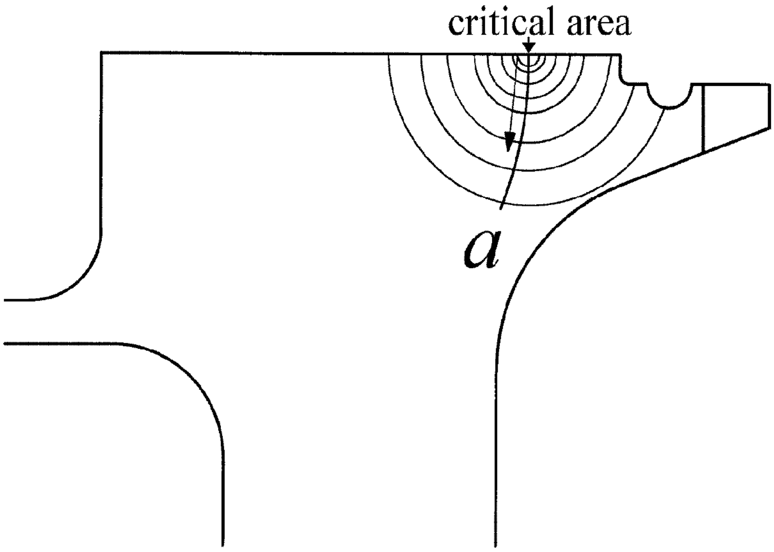

Fig. 15: Propagation of crack front with crack length

manufacturing process or in the application of certain repair methods causing a reduction of the life potential. If shortages of parts occur, it is sometimes inevitable to "Inspect-In-Safety" as a risk management tool. Knowledge gained by recording or monitoring can be used to mitigate the risks. Naturally even the most sophisticated monitoring system or crack propagation prediction cannot really recover life. However a risk evaluation is simplified, if sound statistical information on usage spectra is available.

It may sound surprising, but sometimes it is easier to make statistic statements about the use of engines in a fleet, if the missions are randomly assigned to the available aircraft, as if the missions are assigned aimed at individual aircraft. Sometimes the allocation of certain mission types to individual aircraft cannot be prevented, if e.g. these aircraft are equipped with special electronics, armament etc. On a long-term basis it should be tried however not to always equip these aircraft with the same engines since the underlying assumptions of a risk evaluation otherwise possibly can be

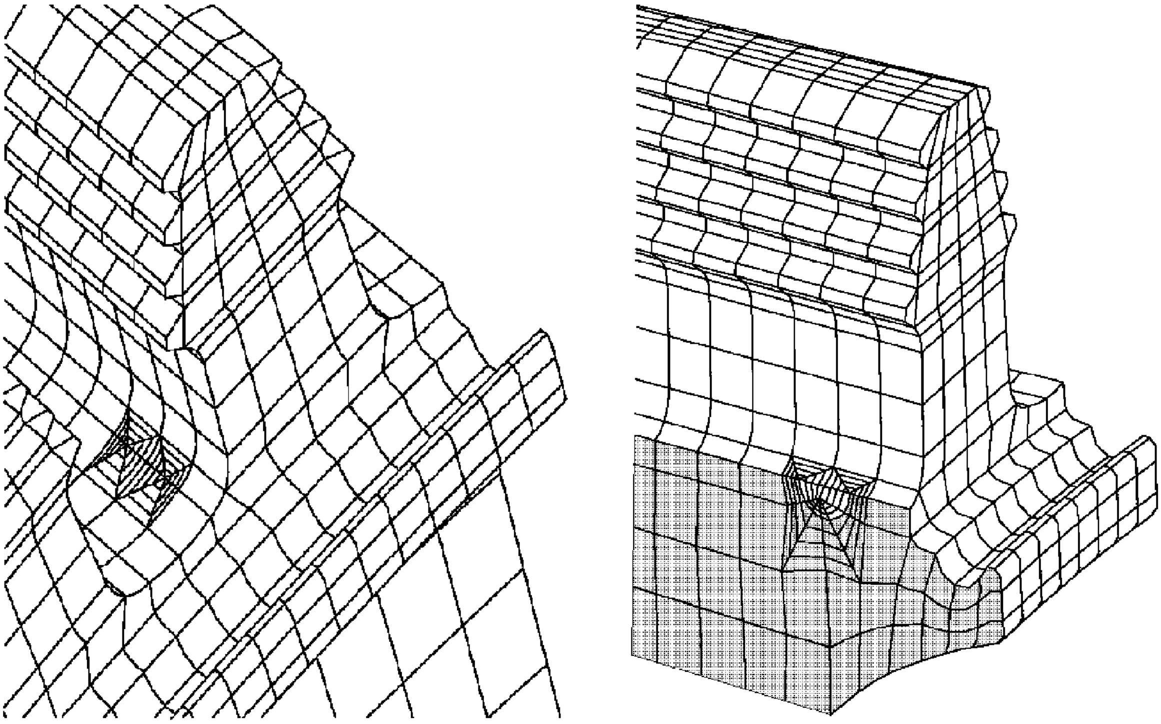

Fig. 16: Locally refined FE mesh for crack growth calculation

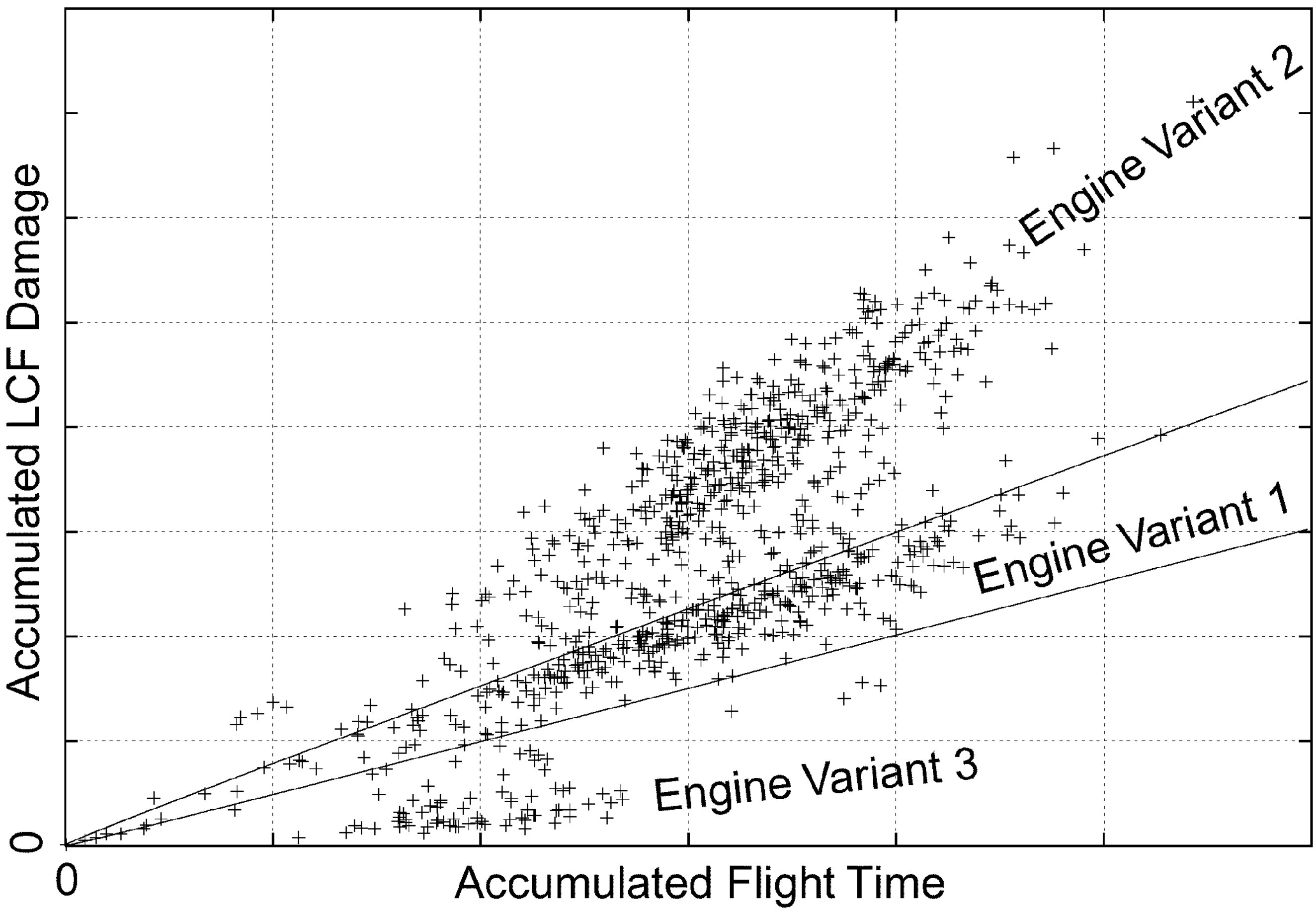

Fig. 17: Accumulated LCF damage for turbine, determined by fleet-wide monitoring

hurt, e.g. if a strongly damaging mission type for the engine is continuously flown. Plans for parts replacement or inspection schedules assuming average usage (e.g. relying on usage distributions like those shown in Fig. 10) may then considerably underestimate the real risk.

Application of fracture mechanical methods to determine safe inspection intervals

Cited from [Suk00]: "The relevance and importance of the computation of fracture parameters and the simulation of three-dimensional crack growth stems from the widespread use of numerical fracture mechanics in fatigue life predictions of safety critical components such as aircraft fuselages, pressure vessels etc. Fatigue failure usually occurs due to the initiation and propagation of surface or near-surface cracks, which are often assumed to be elliptical or semi-elliptical for numerical modelling. Closed-form solutions for the stress intensity factors (SIFs) are available for simple crack geometries in three dimensions; however, for arbitrary-shaped cracks in finite specimens, numerical methods are the only recourse to modelling three-dimensional fatigue crack growth."
Although final knowledge can only be obtained by performing expensive tests, the application of finite element methods to the cracking of components is now within reach. To determine how a crack will propagate from an initial flaw at a critical area of the component, the traditional FE methods have to be enhanced by re-meshing techniques, which adapt the mesh to the crack geometry [Dho98]. Such methods have already been used to predict the crack growth for components, whose life would have been expired, if the classical safe life criteria were applied. One such component was the IP turbine disk of the RB199 engine, for which cracks were found in the rim area. Fig. 14 shows the results of a cyclic spin-pit test, including the application of experimental techniques (marker loads) for a visualization of the crack front. To understand the crack propagation process and to obtain verified data that can be used for a life extension into the crack propagation regime, the crack growth process (Fig. 15) was studied in a 3-dimensional FE calculation. Fig. 16 shows details of the FE mesh used to calculate the crack growth at the bottom of the firtree area of the IP turbine disk. The method is described in more detail in [BK99]. The results of the simulation were compared with the experimental data. A simplified model was developed and implemented in the OLMOS system, thus recovering a considerable amount of usable life.
Recently also methods have become available, that try to avoid the explicit meshing of the crack surface by adding "enrichment functions" to the FE approximation in the vicinity of the crack-tip [Suk00]. The fnite element calculations have to rely on suitable material data, e.g. crack-growth-rate curves as a function of stress intensity factor ranges. There is an urgent need for an extension of the comparatively small database of available crack growth data for engine materials, which is still a field of intensive worldwide research.

Experience from operative engine monitoring systems

Starting around 1980, various monitoring systems have been developed. One of the most comprehensive systems is OLMOS (<u>O</u>n-board <u>L</u>ife usage <u>Mo</u>nitoring <u>S</u>ystem), which is now in use for more than 13 years. This system monitors the fatigue life usage of the engines, the airframe structure and performs a variety of other monitoring tasks. There have been several publications on this system, its architecture and its results, e.g. [BP97]. One of the most important findings was, that such a system is not a static one. The method for tracking the life of critical parts is not necessarily to be held constant during the whole life of an engine. There exist a lot of external and internal factors requiring a continuous adaptation of the life usage monitoring functions [PR95]. The OLMOS is installed in all Tornado aircraft of the German air force. Fig. 17 shows an example of the computed life usage for one critical area on a turbine disk, including all flying engines an also spare parts. The two solid lines show the results of a statistical fleet simulation performed for the engine variant "1", using distribution functions similar to those shown in Fig. 10, that have been derived from recorded flight data. As the turbine disk under consideration is exchangeable between the engine variants, the 3 distinct clouds will continue to diffuse, partially also caused by deliberate decisions of the fleet managers to change disks between the engine variants.

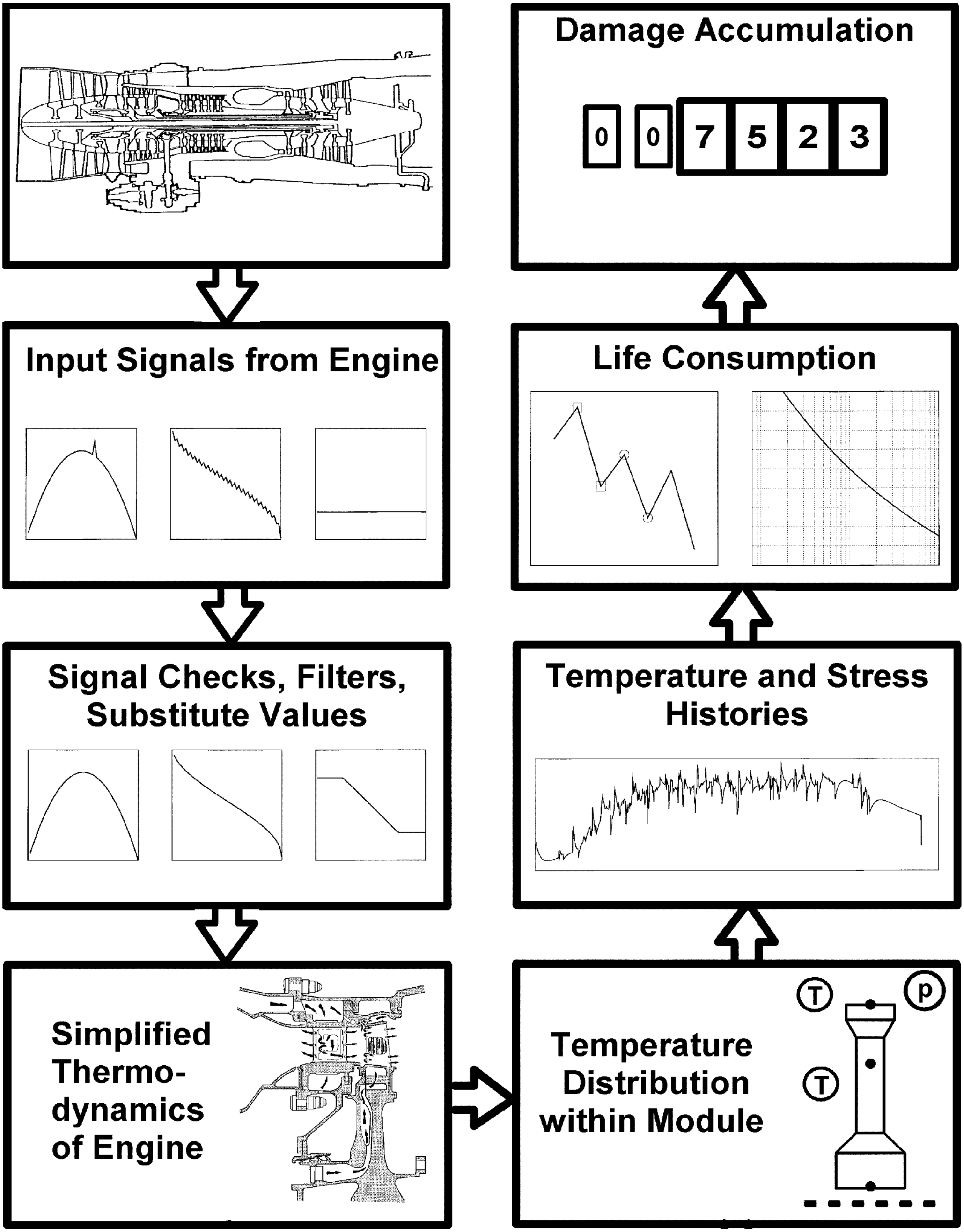

Fig. 18: Overview of life usage monitoring

Requirements for engine monitoring systems

If a new system is defined, there is a wide range of possible architectures. Requirements for an engine monitoring system have to be a balance of the selected benefits and the available capabilities. [ARP1587] provides an extensive list of possible design options. Improved life management would need reliable usage monitoring systems to have realistic stress and temperature cycles [LI98]. Fig. 18 gives an overview of the data acquisition and calculation procedure to be implemented in an engine life usage monitoring system. A comprehensive treatment of all aspects of engine life consumption monitoring is given in [RTOTR28]. The calculation of the usage parameters need not necessarily be performed on-board. It is also possible to use recorded flight and engine data, that are collected on-board and then downloaded by some suitable means (ranging from magnetic tapes to satellite communication links), and do all the processing in a ground station or even at a centralized facility or at industry. We are currently investigating systems, that use highly compressed data storage in the aircraft, to remove the need for frequent downloads. Monitoring systems based on data recording have a potential to remove some of the problems found in the existing on-board systems, e.g. their inability to quickly react on changes in critical areas or the high cost of updates after engine modifications.

Recommendations for fleet usage management

Although carefully planned inspections and the evaluation of usage data are the basic building blocks for a minimum risk extension of aircraft and engine life, the allocation of material can significantly contribute to an acceptable availability of an aircraft fleet. A fleet manager will usually try to avoid that engines have to be removed from an aircraft only because a single fracture critical part has reached its life limit. He will also try to avoid foreseeable engine changes due to parts becoming life-ex, if the aircraft is at some remote base without proper maintenance support. A centralized logistical database containing the life usage data of all flying and spare parts can be used to direct the necessary parts to the right locations at the right time.
For components with a high variability in flight to flight usage there will also be a larger scatter in accumulated life usage for a given range of engine running or flight time. Systematic differences (e.g. those resulting from different thermomechanical environments if the parts are used in engines of different build standards) can lead to distinct clusters of parts in the cycles versus hours plot. Fig. 17 shows an example from the GAF database for one critical area on a turbine disk of the RB199 engine. This area experiences systematically different life usage dependant on the engine variant. The reason is the introduction of engine modifications that had an influence on the spool speed relations between the HP, IP and LP spools. The engine standard present at entry into service corresponds with variant 1. Some years later modifications have been introduced, that led to somewhat higher LP spool speeds. This standard, indicated by “variant 2” is currently the most frequent one. The data marked with "engine variant 3" are from redesigned engines with a new larger fan with a significantly reduced rotational speed of the LP spool. Those engines were introduced 7 years after delivery of the first engine variant. Life usage distributions similar to the one of Fig. 17 have some advantages for fleet life management. The large differences can be taken into account in a parts allocation strategy, which exploits the life potential by clever changes between different engine variants.
If certain critical parts need frequent inspections due to deficiencies in their design, manufacture, material, corrosion resistance or fatigue life, those inspections may become a decisive cost factor. In [WB97] an example is given for the F100-PW-100 engine. For this engine failures of the third-stage fan disk lug resulted in uncontained fan blade liberations. The frequent ultrasonic inspections of the disk lug, that had to be performed to keep the risk acceptable were reported to have become the No.1 maintenance man-hour driver in the F100. The solution was to incorporate new zero-time disks to gain some inspection-free time until redesigned disks and blades became available.

The management of parts has to take into account long-term plans for fleet size. Many air forces are now considering to reduce fleet sizes far below the figures planned and acquired at the end of the cold war era. A balance has to be found between affordable peace time operation and high availability during a potential crisis. It is not always economical to use the full life potential of all parts. It is noted in [TH98] that it may be sometimes advantageous to scrap parts a considerable time before their life is expired, if the cost of engine disassembly, downtime etc. is considered. This will also reduce cost due to handling, depot operation and administration.

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